Scientific Progress in Biomolecular Materials

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In honor of Mike Markowitz

DEPARTMENT OF ENERGY • UNITED STATES OF AMERICA

Northwestern University

Outline

Borrowed from the Biomolecular Materials Program (Dr. Aura Gimm), I will cover examples of materials:

1) that display complex yet well-coordinated collective behavior…………
2) capable of functioning under harsher, non-biological environments………….
3) that coherently and actively manage multiple complex and simultaneous functions ……………

Inspiration from nature

“………Biology provides a blueprint for translating atomic and nanoscale phenomena into mesoscale materials….”

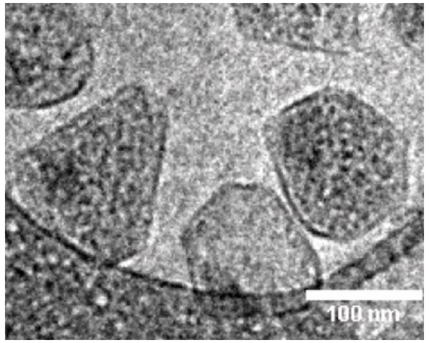
- Respond to environment changes (**chemicals, light, electric fields**)
- Locomotion and force generation
- Energy efficiency (dissipation in non-equilibrium conditions)

Embryonic growth of a salamander

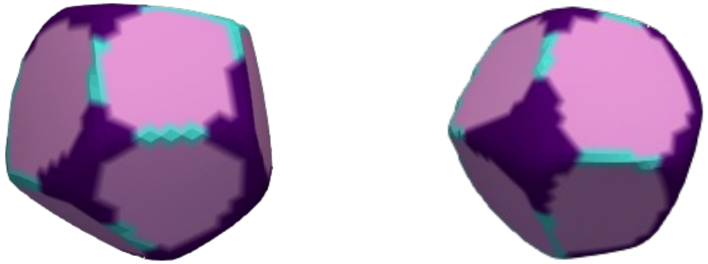
Jan van Ijken; Short film: Becoming

Buckling in multicomponent membranes

Nanoscale: Solid-solid domain patterning in polyhedral bacterial microcompartments

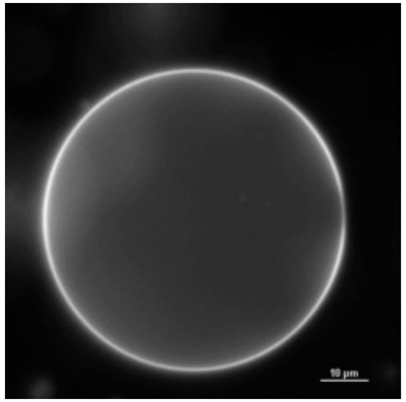


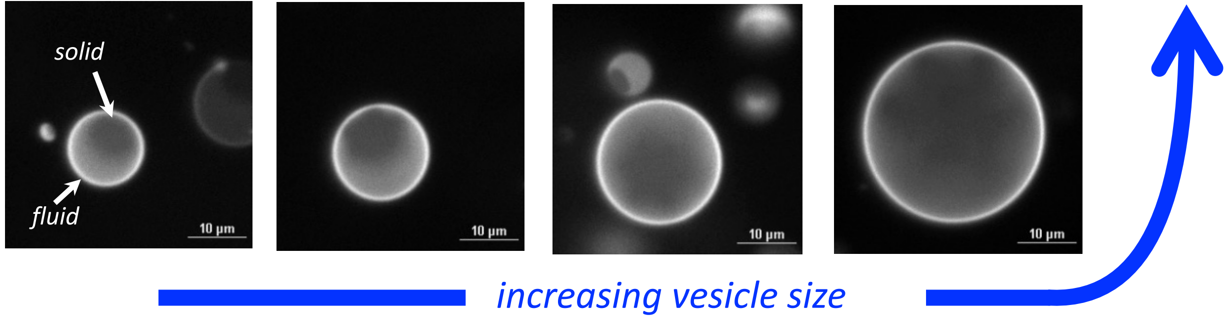
C. E. Mills, C. Waltmann et al Nature Comm. 13, 3746 (2022)



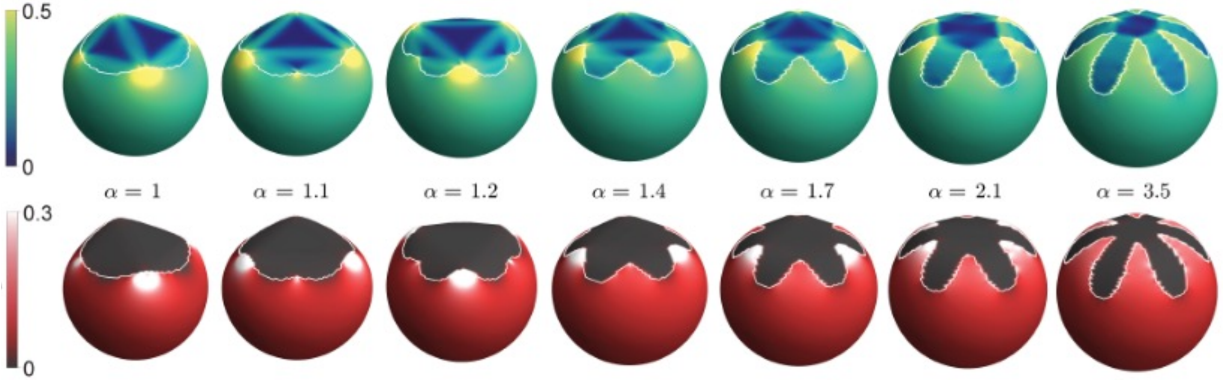
C. Waltmann, A. Shrestha, M. Olvera de la Cruz

Micron-scale: Fluid-solid domain patterning





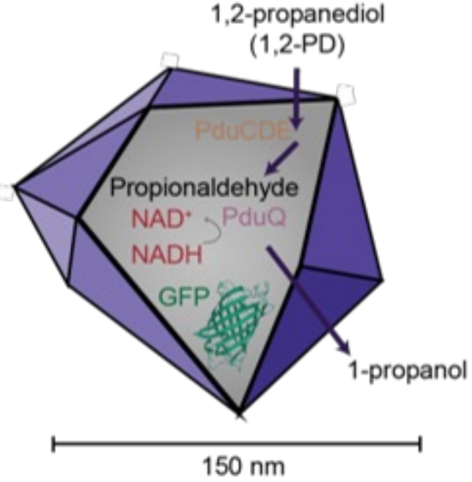
increasing vesicle size

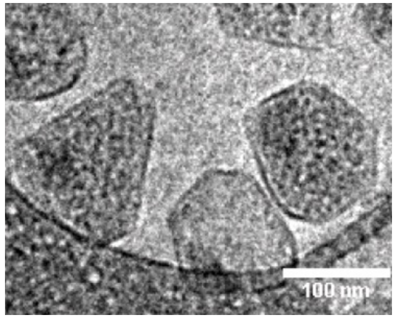


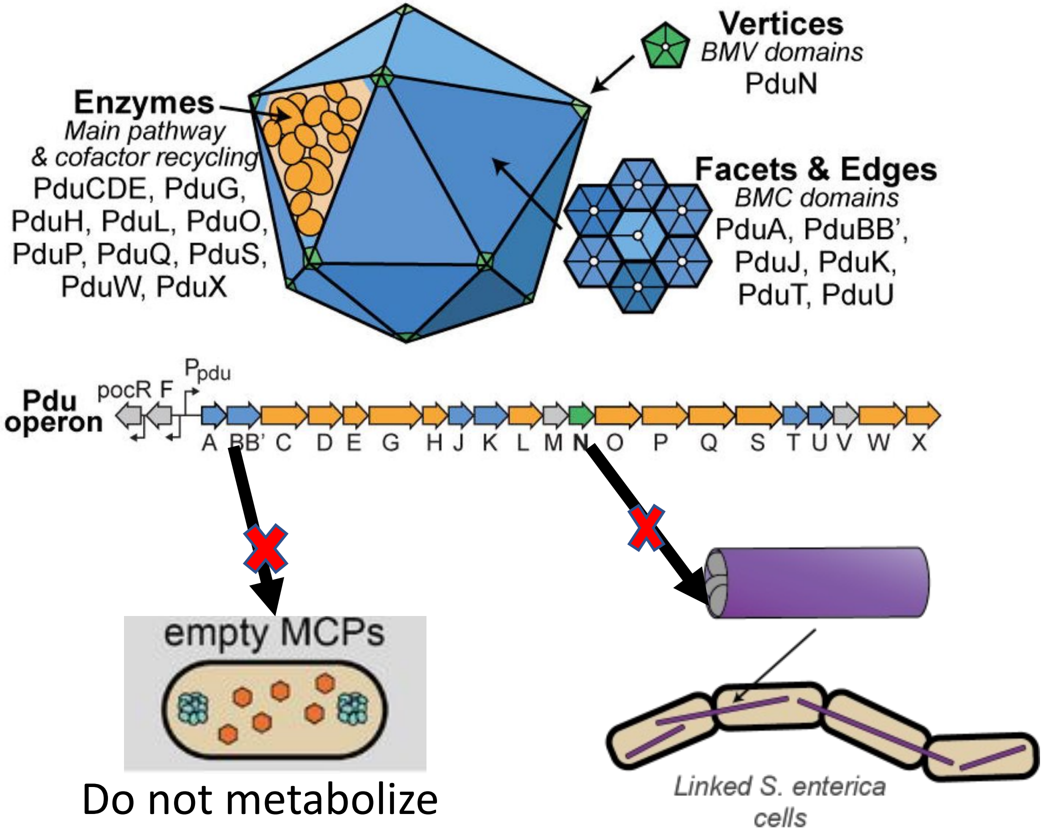
Wan, Jeon, Xin, Grason & Santore,

Nanoscale enzymatic crystalline membranes

In bacterial cells, protein aggregates organize the local environment to promote chemical reactions. These bacterial microcompartments (MCPs) are polyhedral shells that help bacteria survive in harsh environments.







Do not metabolize the reactant

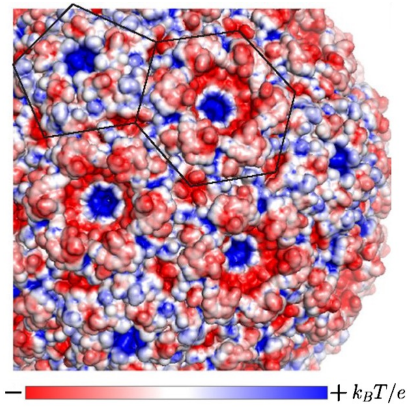
Metabolize but do not reproduce

The *Salmonella enterica pdu* operon contains the genes encoding the Pdu shell proteins. We design protein mutations or deletions to assemble shell morphologies with specific functions

Y. Li et al. *ACS Central Science* 7, 658–670 (2021).

C. E. Mills, C. Waltmann et al. *Nature Comm. 13, 3746 (2022)*

Atomistic simulations suggest a segregation between the most common shell proteins, which suggests shell surface charged patterns even native and mutated proteins

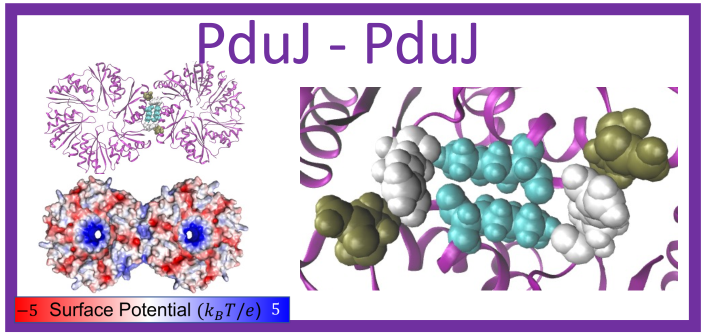


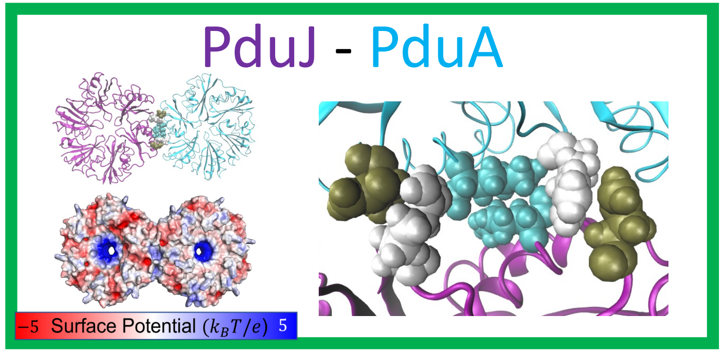
M. Sutter et al., Plant Physiol. (2019)

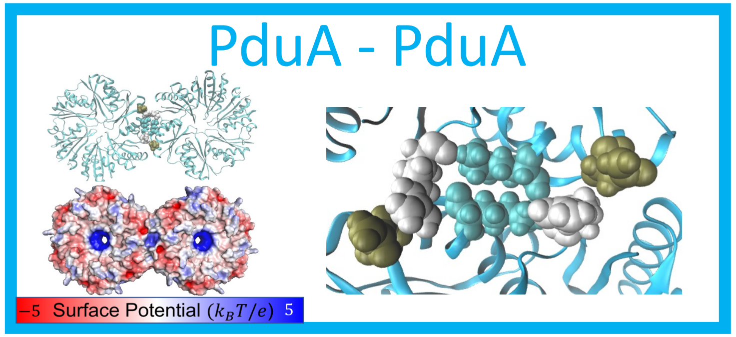
Continuum elasticity models

In icosahedral shells
S. Li et al *ACS Nano* 2021

The polyhedral shells patterns

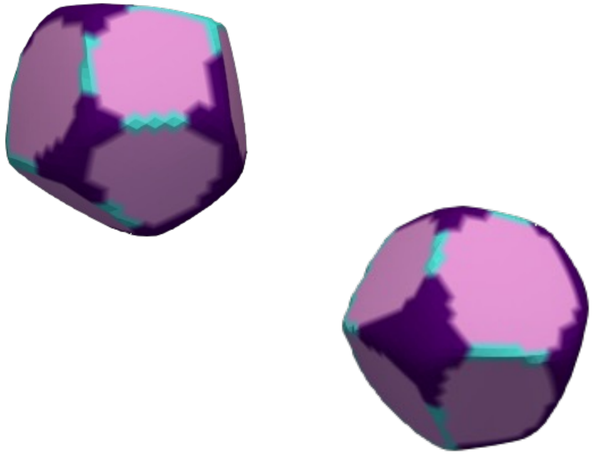






The protein net charges:
hexamers PduA= 0, PduJ= -6,
pentamer PduN=-10,
hexameric trimer PduB= -21.

A. Gomez, C. Waltmann, C. Mills et al , in preparation



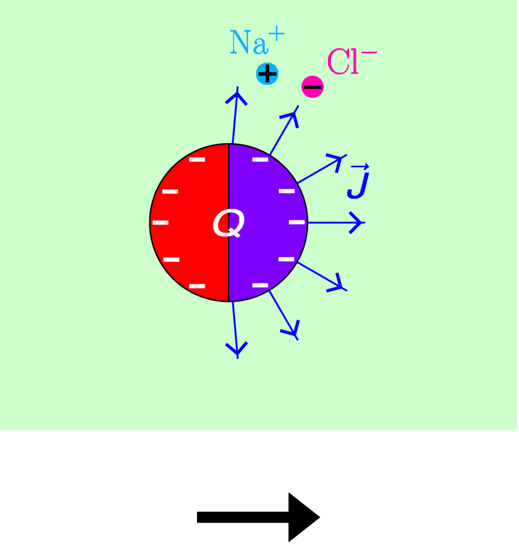
We can design certain patterns once we explore the functions of these patterns

MCPs are chemotactic in self-free conditions!

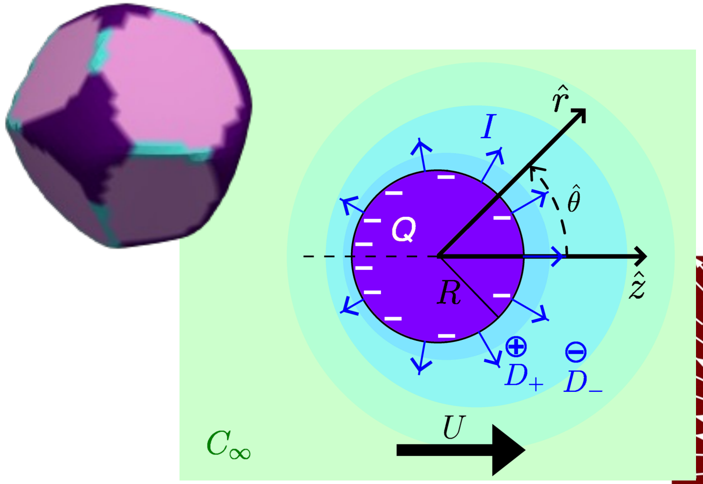
C. Waltmann, A. Shrestha,
M. Olvera de la Cruz,
arXiv:2307.12834 (2024)

Self-phoretic motion induced by surface charge asymmetry

In micron size particles self-ionic diffusiophoresis is possible at nearly zero salt when flux is asymmetric (Urease-powered colloids or photo-activated AgCl Janus particles)

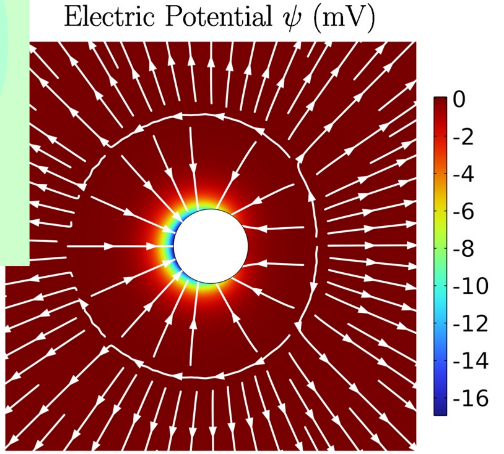


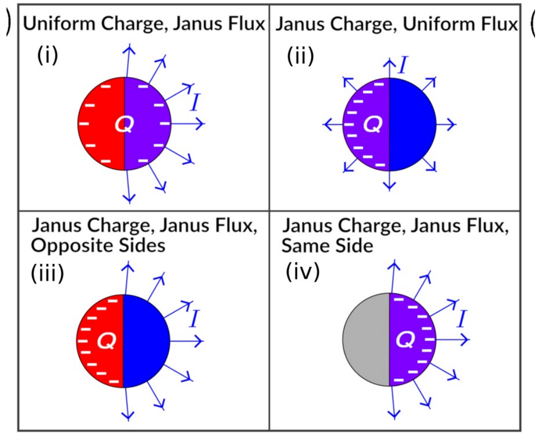
We found directed self-propulsion through asymmetric surface charge even when ionic flux is uniform at the nanoscale, which is very hard!



$$\boxed{U_{\sigma_-} \approx \frac{\alpha I Q}{R} f(\kappa R)}$$

$$\alpha = e(D_+ - D_-)/16\pi\varepsilon\eta D_+ D_-$$



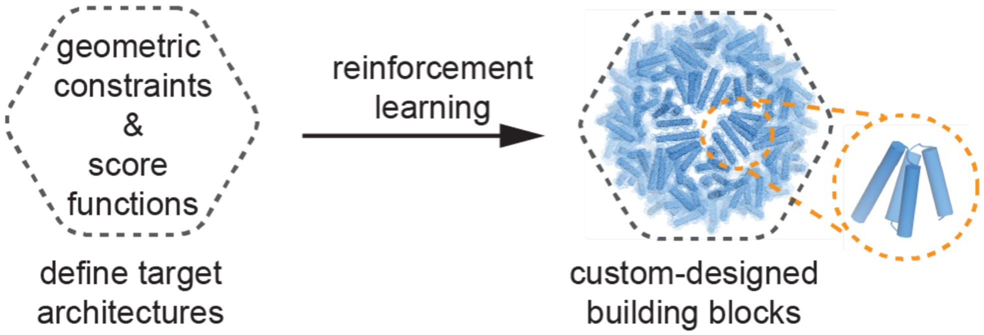


Particles with Janus surface charge and ion flux on opposite hemispheres (iii) leads to optimally high phoretic speeds in the order of µm/s or higher.

A. Shrestha, M. Olvera de la Cruz, Phys. Rev. E (2024)

Mimics of biological structures

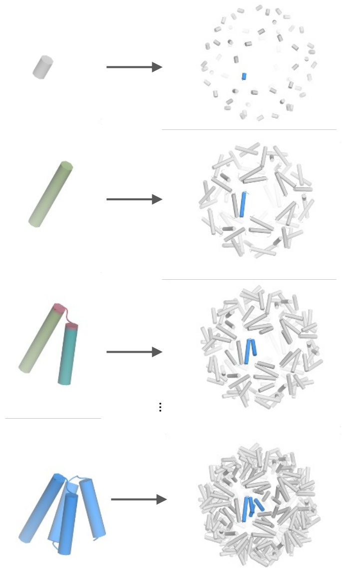
Protein design with reinforcement learning


geometric constraints & score functions

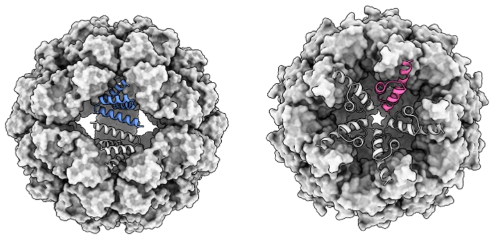
define target architectures

reinforcement learning

custom-designed building blocks



Experimental success



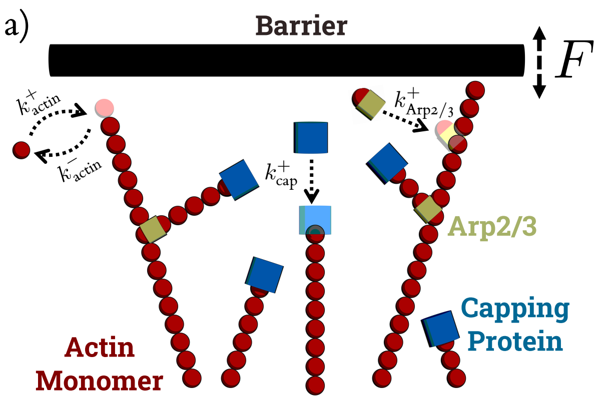
2.5 Å Cryo-EM structure

Lutz, I.*; Wang, S.*†; Norn, C.*; et al (D. Baker). *Science* **2023**

Dissipation and control in nonequilibrium self-assembly

Reinforcement learning to control material properties

Actin polymers grown under applied load



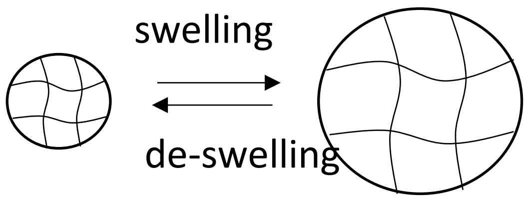
A minimal model of actin growth under load recapitulates experimental observations and demonstrates opportunities for nonequilibrium control.

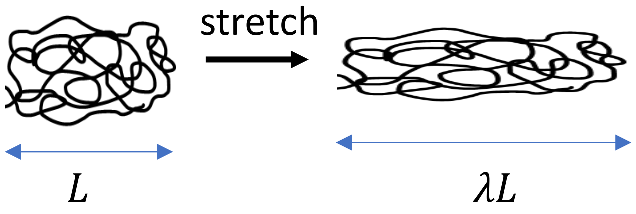
Chennakesavalu, S. et al. (G. M. Rotskoff) PNAS (2024)

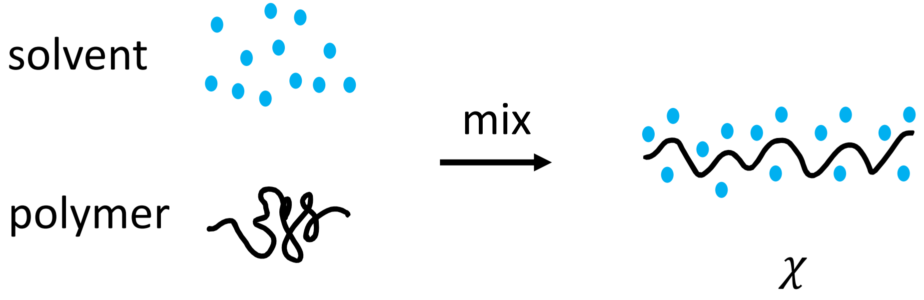
Responsive enzymatic microcompartments

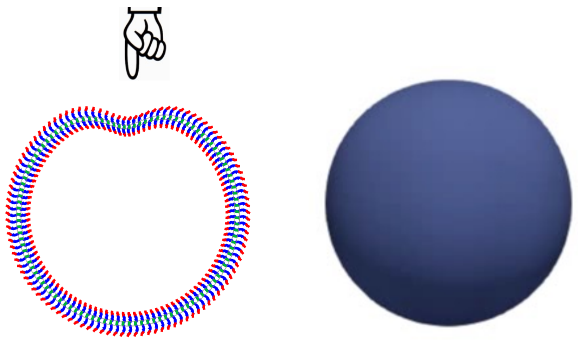
Chemo-mechanical coupled gel model, an example is a Belousov–Zhabotinsky (BZ) reacyion inside a gel or polymer brush leads to self-oscillations that expand and contract the polymers (see T. Masuda et al. *Langmuir* 2018, 34, 4, 1673–1680)

Functionalized membrane with a catalyst undergoing an oxidation-reduction (Oregonator model) reaction





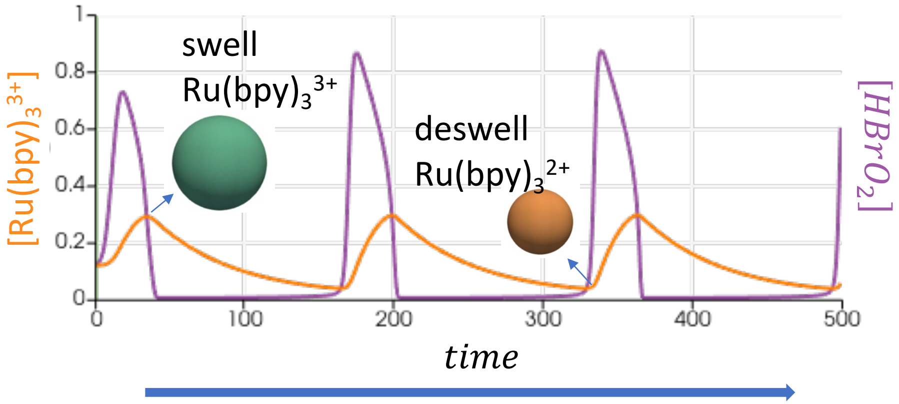




$u = [\mathrm{HBrO_2}]$

$v = [oxidized\ catalyst]$

$D_u \rightarrow diffution\ coefficient$



Autonomous swell-deswell

S. Li, et al (Olvera de la Cruz) *PNAS* 118 (10), e2025717118 (2021)

Geometric Feedback

$v = [oxidized\ catalyst]$

$u = [\mathrm{HBrO_2}]$

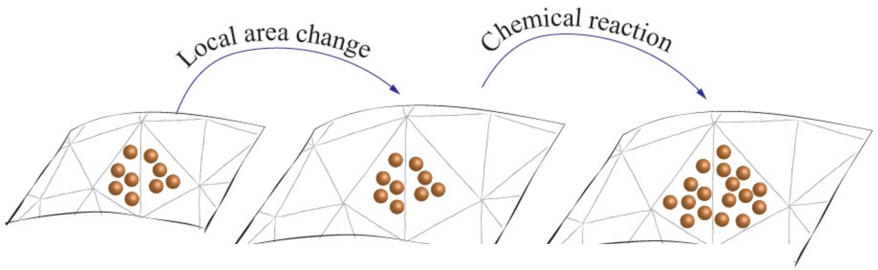
When v increases the membrane

Target metric change by

$$M(v) = 1 + \alpha\, v(r,t)$$

Concentration = Number of molecules / Area

Local change in area → change in chemical concentrations



Pattern formation in response to small random fluctuations in local area.

Mechanically triggered pattern formation

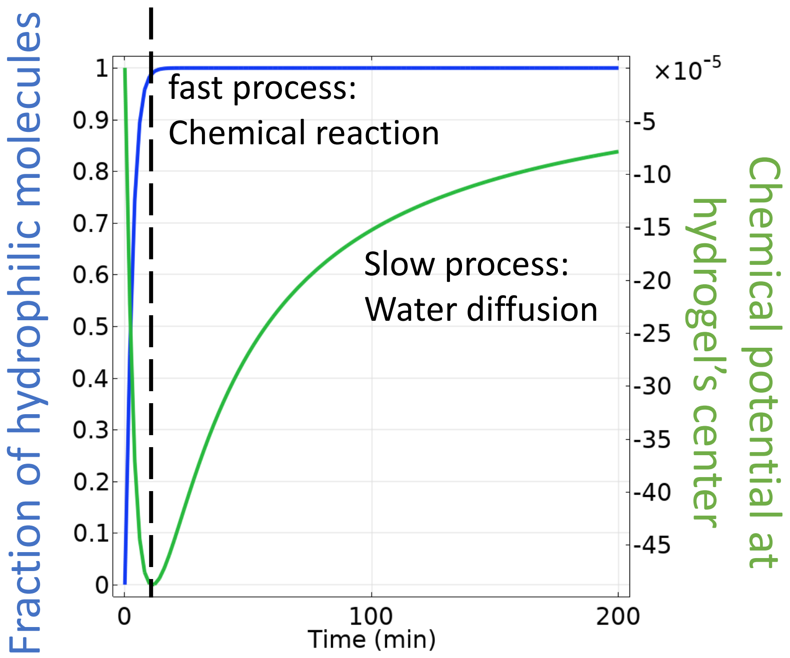
$f = 0.6$ (reduction wave outspeeds the oxidation wave), $D_u = 1\,a^2/\tau$, $\alpha = 1$

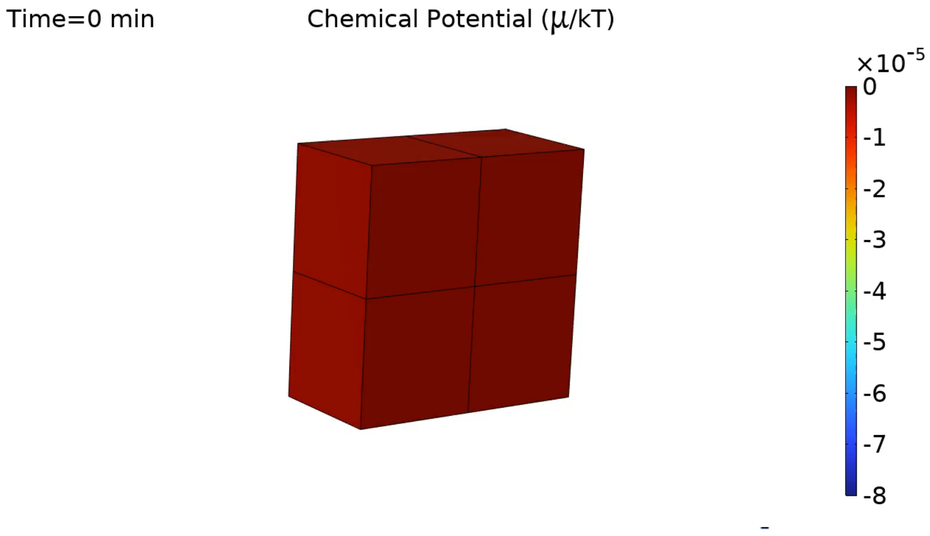
$f = 1.0$ (oxidization wave outcompetes the reduction wave), $D_u = 1\,a^2/\tau$, $\alpha = 1$

Pattern formation can be controlled by chemical and mechanical properties of the material

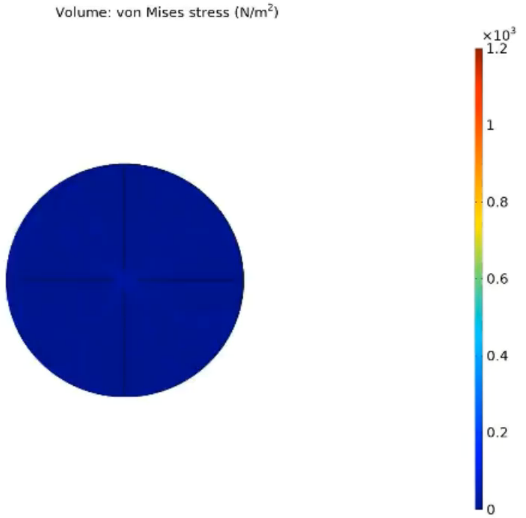
Modeling the transient behavior of chemically responsive gels

Volumetric change lags behind the chemical reaction due to the slow water diffusion

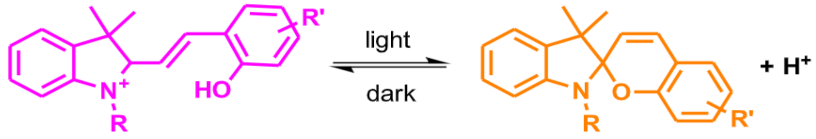




Simulating a hydrogel shell with fixed inner core volume



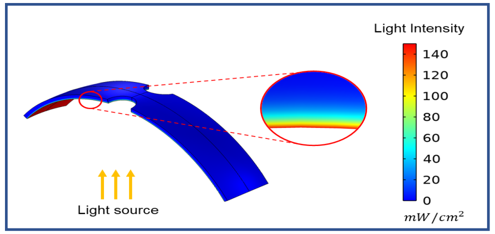
Same process in light responsive hydrogels



Merocyanine (MCH$^+$)
(hydrophilic)

Spiropyran (SP)
(hydrophobic)

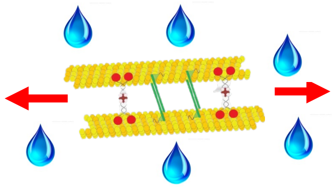
Light actuation

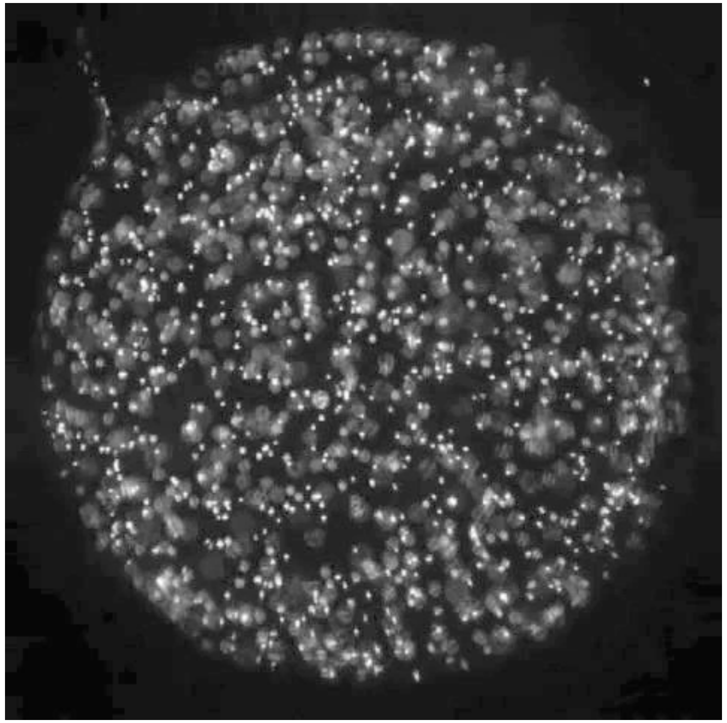


Cell function mimics (Michael F. Hagan, Seth Fraden, Pengyu Hong (Brandeis) and Zvonimir Dogic (UCSB))

Machine learning approaches to understanding and controlling 3D active matter

microtubules
(MTs) +
kinesins
motors



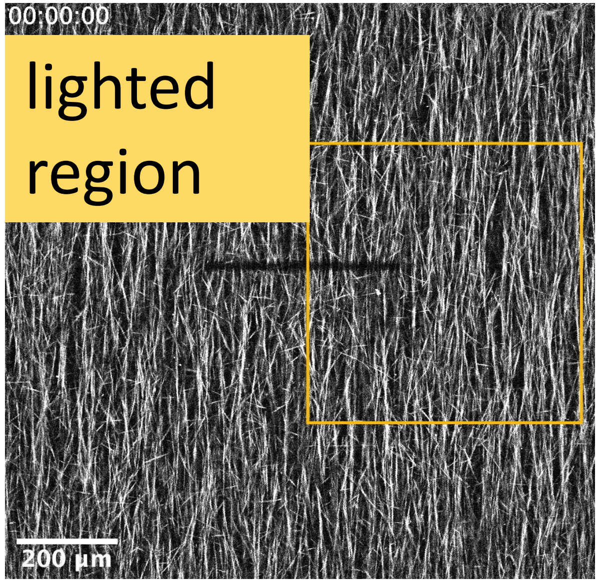


Cytoplasmic streaming

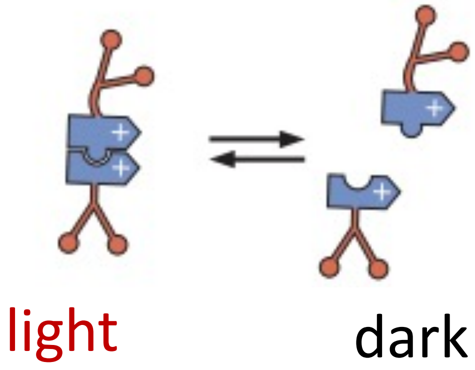
Isolated kinesin motors consume ATP and walk along microtubules.
When photoactivated motor pairs dimerize increases, increasing sliding:

Motor clusters active only when bound (**light on**)

Optical control of motor activity in space and time

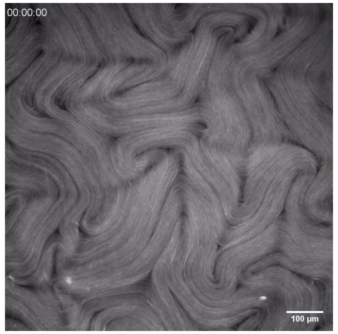


Lemma, Varghese, Ross, Thomson, Baskaran, Dogic PNAS (2023)



-Data-driven discovery of accurate physics-based models, combined with optimal control theory
-Deep learning tools to forecast and control dynamics

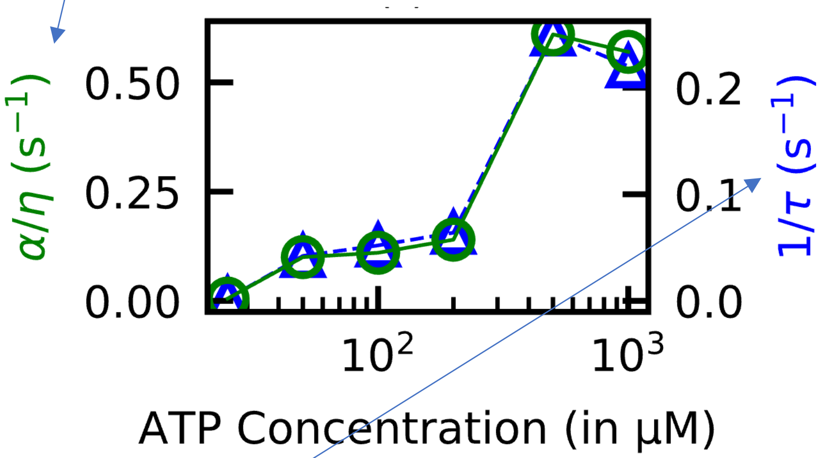
Data-driven model discovery



Microtubules + kinesin molecular motors data (Sanchez et al Nature 2012)

NEW: Use Sparse Identification of Nonlinear Dynamics (SINDy)

SINDy gives activity strength as a function of [ATP]!



inverse of velocity correlation time (independent measurement from experiment)

C. Joshi, et al (Dogic & Hagan) *Phys. Rev. Lett. (2022).*

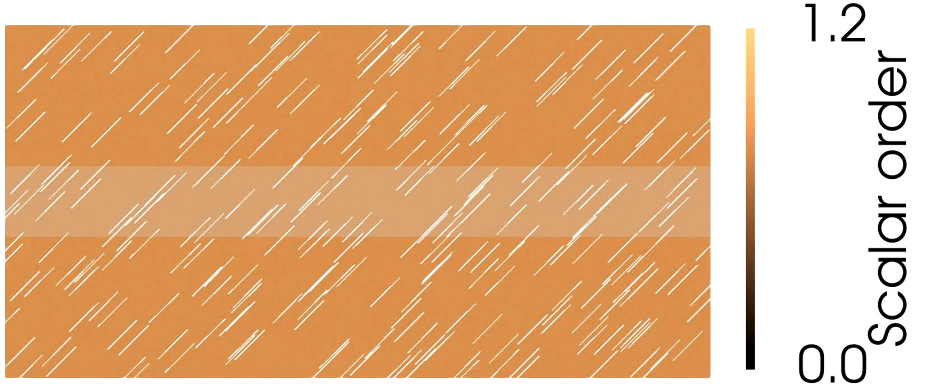
Optimal control finds new behaviors

Coherent flow in a “channel” with walls made of light

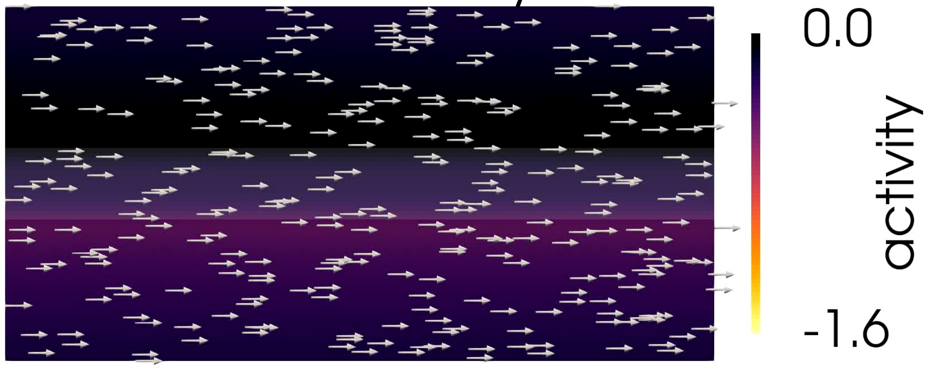
-Counter-rotating vortices in the bulk create flow in the “channel”

-obtains a behavior that is not an attractor!

lines = director field orientation



arrows = velocity

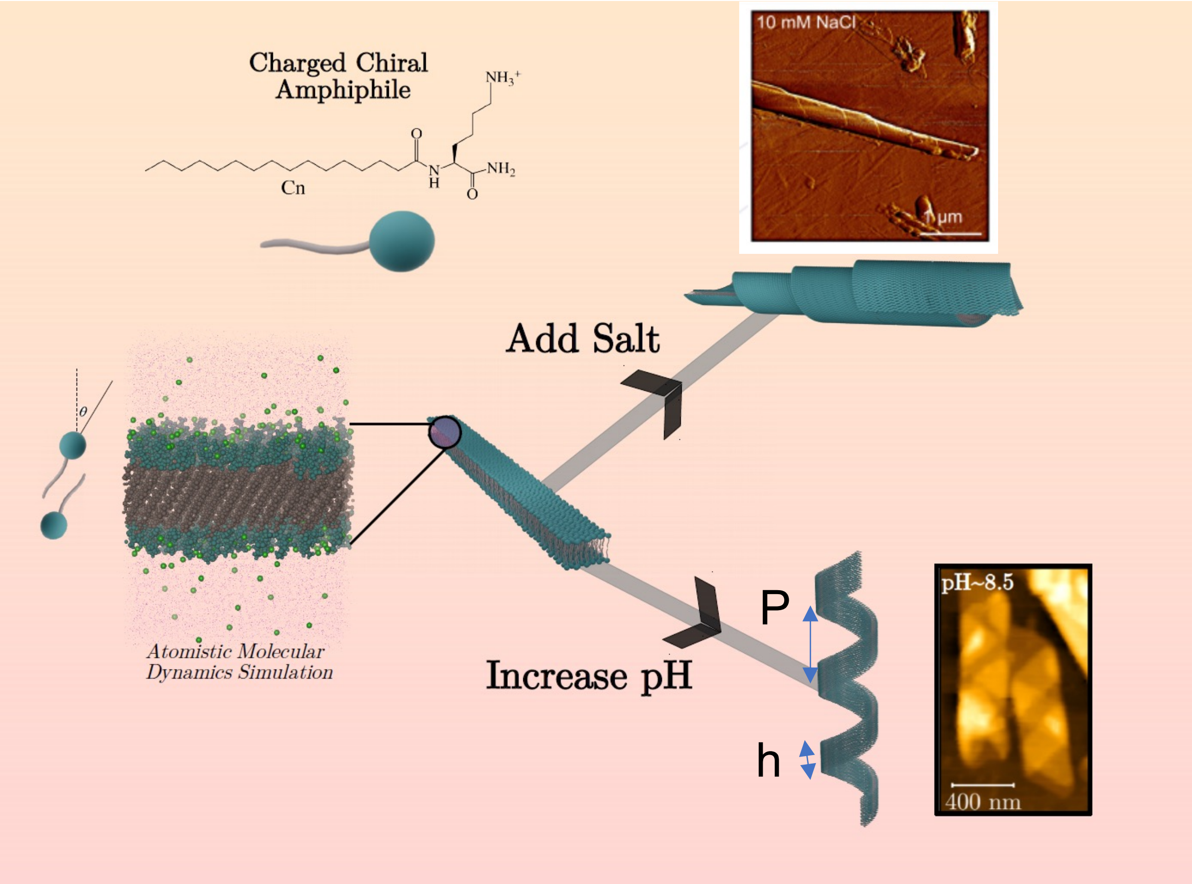


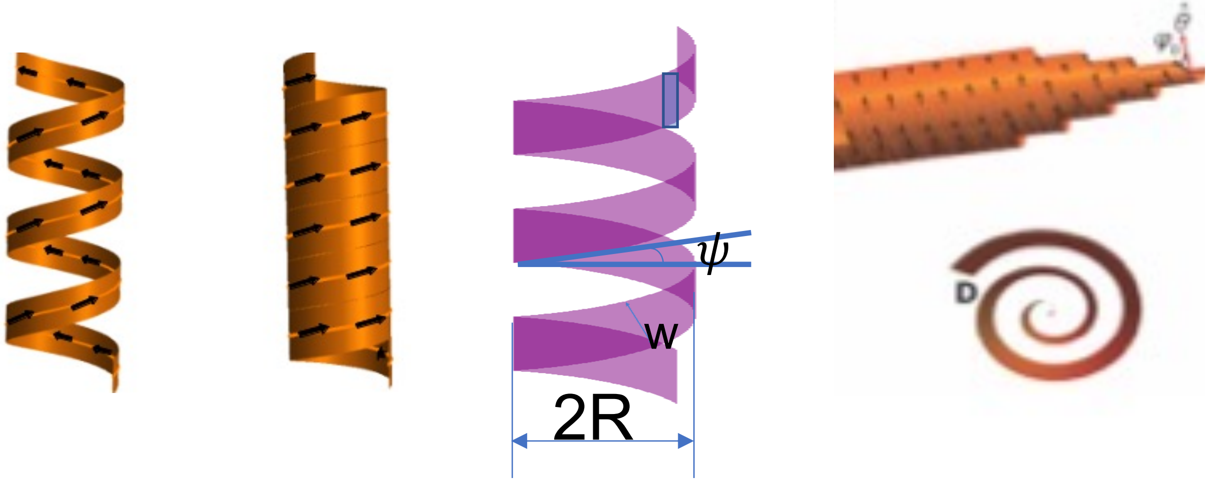
Ghosh, Norton, Hagan, Baskaran (in prep.)

Electrolytes and membranes

Biological structures have impressive functionalities that require the organization of heterogeneous molecules into mesoscale structures with broken symmetries.

Chirality symmetry breaking is ubiquitous in biology at a molecular level with only few examples at the mesoscale. By a combination of theory, simulations and experimental characterization, we found helical and helicoidal scroll membranes at the mesoscale only when right- or left-handed chiral peptide amphiphiles assemble. Racemic mixtures lead to flat bilayers.



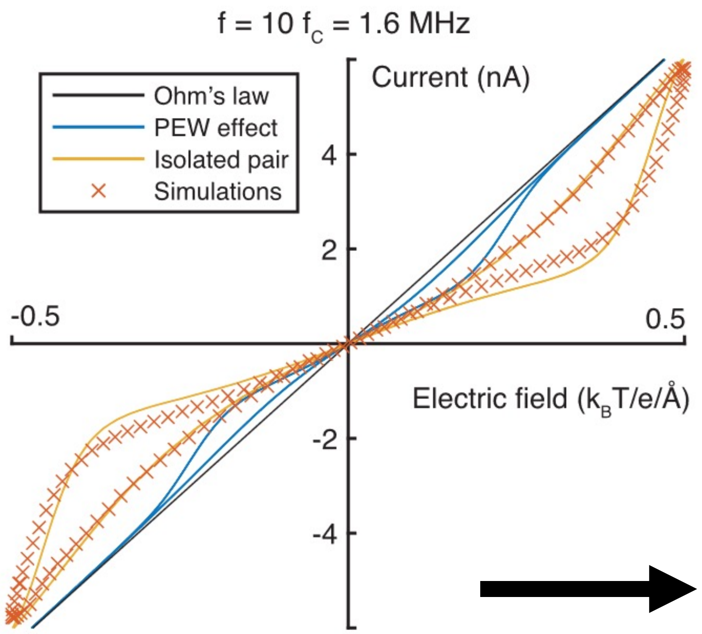


$$P = 2\pi R \tan\psi$$
$$h = w/\cos\psi$$

McCourt, et al ACS Central Sci. 8, 1169-1181 (2022)

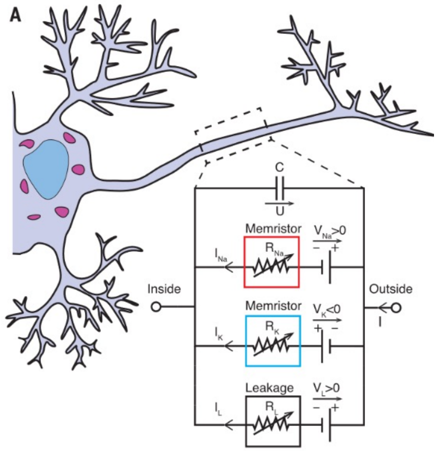
PI: Monica Olvera de la Cruz; co-PI: Michael J. Bedzyk, Northwestern University

Non-linear ionic transport phenomena
Ionic machines



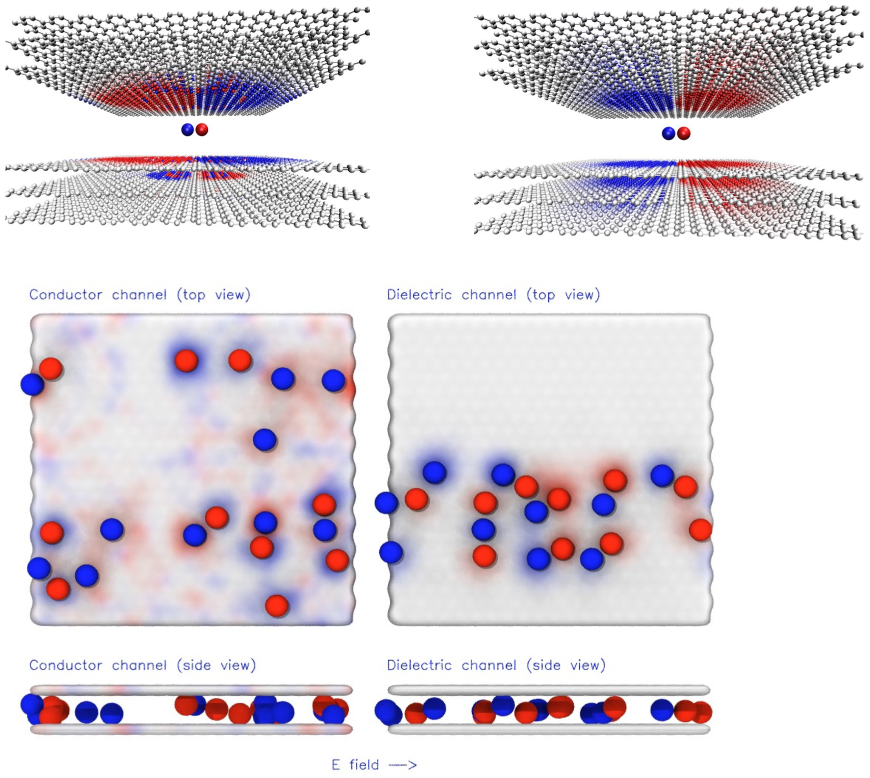
Non-linear transport phenomena

Robin, et al. *Science* 373 (2021)



Neural emulation

Neuromorphic computing for AI



In strong confinement the ionic conductivity is non-linear (F. Jiménez-Ángeles, et al. *Faraday Discus.* 246, 576–91 (2023))

Today we can include pH effects in computer simulations, beside polarization effects.

Thanks